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Research papers

A new normal for streamflow in California in a warming climate: Wetter wet seasons and drier dry seasons

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ABSTRACT

In this study, we investigate changes in future streamflows in California using bias-corrected and routed streamflows derived from global climate model (GCM) simulations under two representative concentration pathways (RCPs): RCP4.5 and RCP8.5. Unlike previous studies that have focused mainly on the mean streamflow, annual maxima or seasonality, we focus on projected changes across the distribution of streamflow and the underlying causes. We report opposing trends in the two tails of the future streamflow simulations: lower low flows and higher high flows with no change in the overall mean of future flows relative to the historical baseline (statistically significant at 0.05 level). Furthermore, results show that streamflow is projected to increase during most of the rainy season (December to March) while it is expected to decrease in the rest of the year (i.e., wetter rainy seasons, and drier dry seasons). We argue that the projected changes to streamflow in California are driven by the expected changes to snow patterns and precipitation extremes in a warming climate. Changes to future low flows and extreme high flows can have significant implications for water resource planning, drought management, and infrastructure design and risk assessment.

1. Introduction

Excessive deviation from the normal hydrological condition in river systems can impose catastrophic socioeconomic impacts (e.g., fatalities, infrastructure and property damage, agricultural loss, and disruption of daily life) and challenge the existing water management plans (e.g., Demaria et al., 2016; Nazemi and Wheater, 2014). Current methods for design of hydraulic structures (e.g., dams, bridges, levees, spillways, culverts) are based on the so-called stationary assumption that assumes the statistics of extremes and distribution of the underlying variables do not change over time (Sadegh et al., 2015). The stationarity assumption requires that the distribution of past observed events and the statistics of observed extremes are a good representative of possible future conditions (e.g., Koutsoyiannis, 2006; Read and Vogel, 2015; Villarini et al., 2009). However, in recent years, studies have shown that different natural and anthropogenic factors (e.g., land use land cover, climate, urbanization, watershed modification) can alter streamflow characteristics (Alfieri et al., 2015; Beighley et al., 2003; Hailegeorgis and Alfredsen, 2017; Krakauer and Fung, 2008; Luke et al., 2017; Mallakpour et al., 2017; Mallakpour and Villarini, 2015; Villarini et al., 2015), thus questioning the validity of the stationary assumption (Cheng et al., 2014).

The projected warming and expected changes in precipitation and snow patterns are anticipated to change river flows (e.g., Alfieri et al., 2015; McCabe and Wolock, 2014; Nazemi and Wheater, 2014). A warmer climate is expected to intensify the hydrological cycle, increasing the frequency and/or intensity of extreme events such as droughts and floods (e.g., Das et al., 2013; Milly et al., 2005; Pachauri et al., 2015; Voss et al., 2002; Wang et al., 2017). Warmer land surface and water bodies may increase evaporation (Scheff and Frierson, 2014), and enlarge atmospheric moisture holding capacity (the Clausius–Clapeyron relation; O'Gorman and Muller, 2010); both of which can contribute to the changes in river flows (e.g., Alfieri et al., 2015).

Moreover, a warmer climate may drive earlier snowmelt, decline in snowpack, change in seasonality of river flows and changes in snow to rain ratio (e.g., Cayan et al., 2001; Harpold et al., 2017; Knowles et al., 2006; Mao et al., 2015; Neelin et al., 2013; Stewart et al., 2005). These changes are even more important in regions like California, where streamflow relies on winter snow accumulation (e.g., Diffenbaugh et al., 2015; Li et al., 2017). Several studies have documented that warm and wet storms brought by atmospheric rivers (AR) during winter may cause severe flooding in California (e.g., Barth et al., 2016; Dettinger, 2011; Leung and Qian, 2009; Ralph et al., 2013). Jeon et al. (2015) used 10 CMIP5 climate models to show that AR events in

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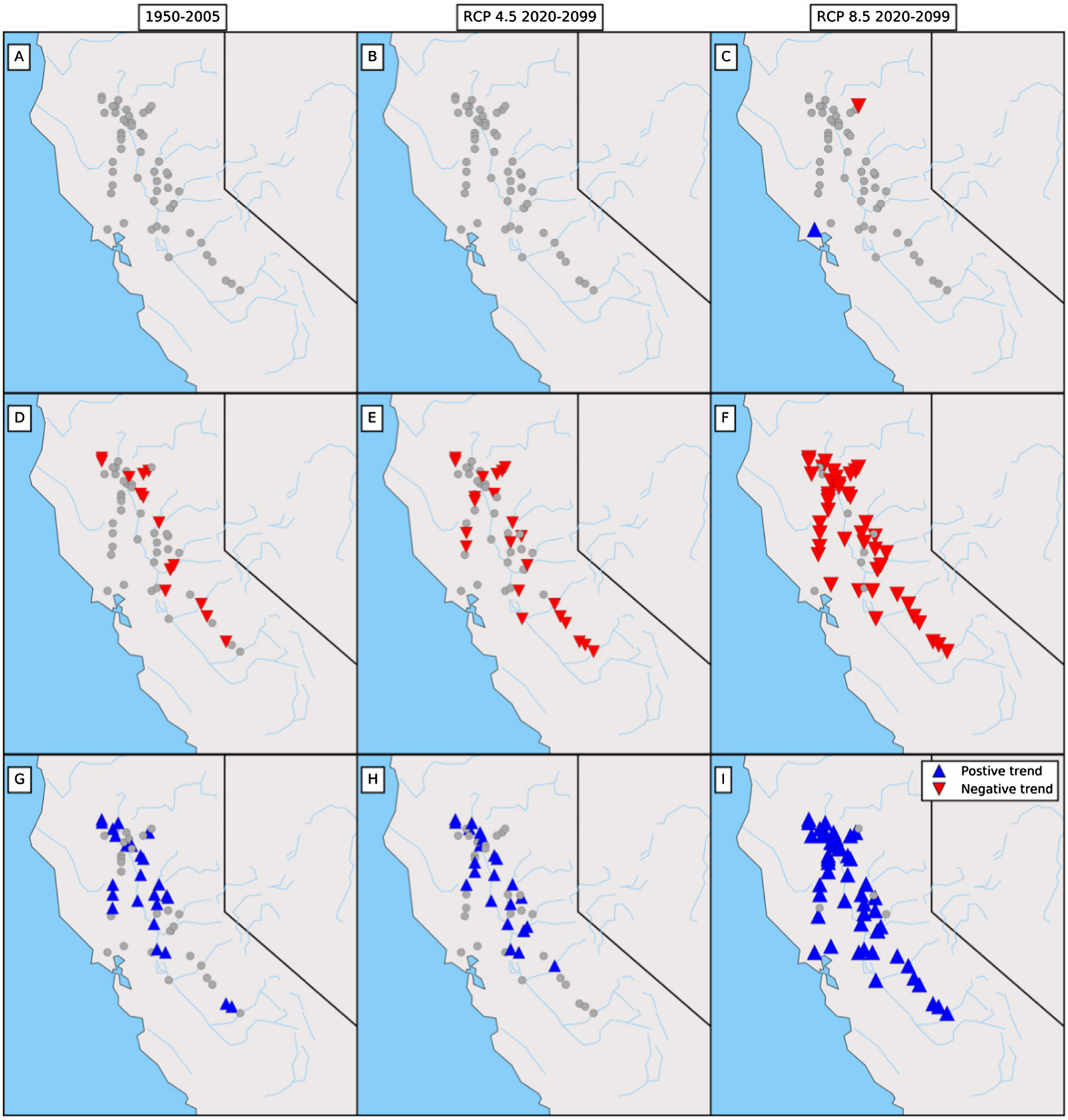

Fig. 1. Statistically significant trends in the annual mean (panel A-C), annual minima (panel D-F) and annual maxima (panel G-I) flows over Northern California. Left panels summarize the results for the historical baseline period. Middle and right panels represent change in the projection period under the RCP 4.5 and 8.5 scenarios, respectively. Positive and negative trends are presented with upward blue, and downward red triangles, respectively. The grey circles show sites with no statistically significant trend at 0.05 level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

warming climate would bring more frequent and severe storms to California in the future. Similarly, Payne and Magnusdottir (2015) used 28 CMIP5 models in a study where they projected up to 35% increase in AR landfall days. Dettinger (2011) have shown that potential increases in the magnitude and frequency of AR events in the future can cause more severe and frequent flooding events in California.

In recent years, California has experienced a series of flooding events (Vahedifard et al., 2017) on the heels of a 5-year drought (e.g., AghaKouchak et al., 2014; Hardin et al., 2017; Shukla et al., 2015). In 2017, a major flood in Northern California led to structural failure of Oroville Dam's spillway that triggered the evacuation of about 200,000 people. In another event, a levee breach near Manteca, CA, provoked the local government to evacuate about 500 people (Vahedifard et al., 2017). In light of the occurrence of recent extreme events over Northern California, this study aims to answer a simple but important question: how will streamflow distribution change for Northern California under a warming climate? The insights gained by improving our understanding of the possible changes in the direction and magnitude of streamflow can have profound implications on adaptation strategies to cope with the future extreme events (i.e., floods and droughts) and better managing of the water resources (Villarini et al., 2015).

Several studies have previously investigated projected changes in the hydrologic cycle over California from different perspectives (AghaKouchak et al., 2014; Ashfaq et al., 2013; Burke and Ficklin, 2017; Diffenbaugh et al., 2015; Hailegeorgis and Alfredsen, 2017; Li et al., 2017; Thorne et al., 2015; Zhu et al., 2005). Our current state of the knowledge is mostly limited to possible changes in average annual, annual maxima or seasonal streamflow mainly using gridded runoff products. While most studies reported changes in seasonality of streamflow over California, there is no consensus on the direction (sign)

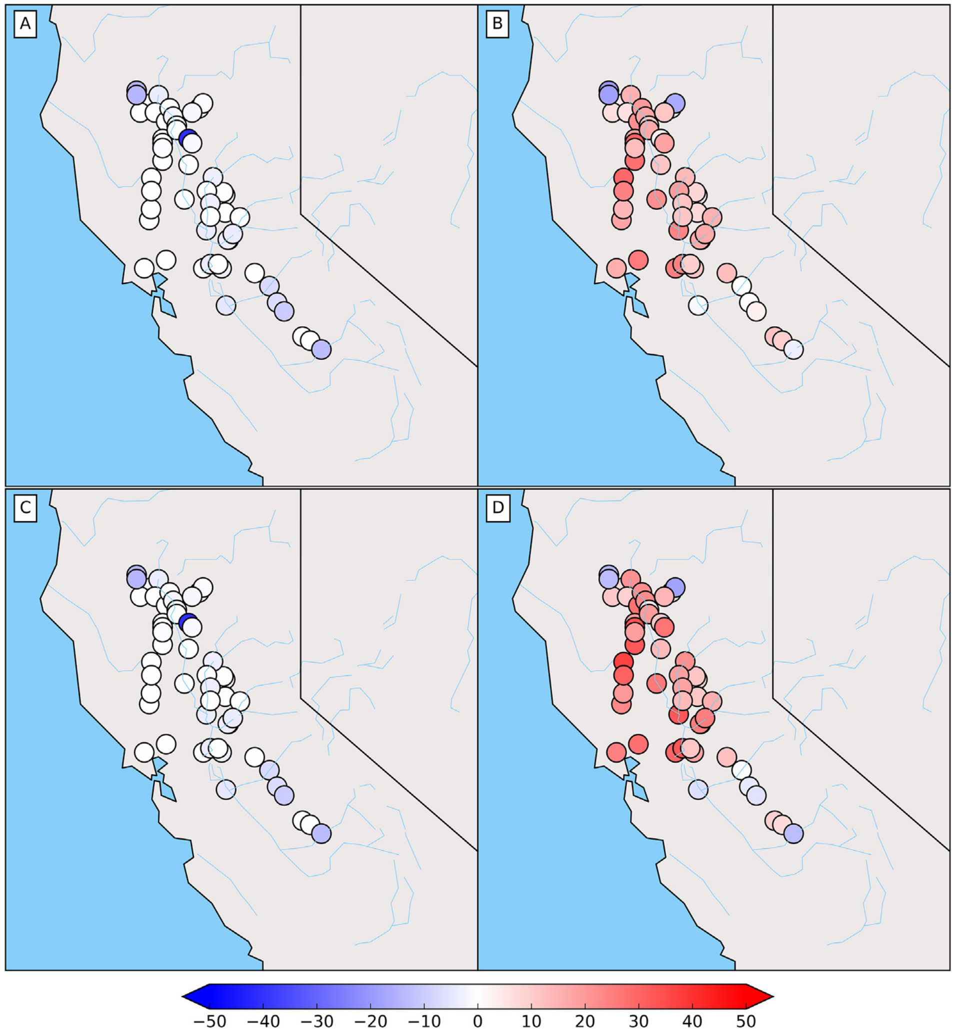

Fig. 2. Percent change [%] in the magnitude of 7-day low flows (left panels) and 7-day high flows (right panels) relative to the historical period for the RCP 4.5 (top panels) and RCP 8.5 (bottom panels).

of change in the flow regime. Some studies projected little or no change in future annual streamflow over California (e.g., Regonda et al., 2005; Stewart et al., 2005; Thorne et al., 2015), while others projected a decreasing trend in streamflow (e.g., Berghuijs et al., 2014; Das et al., 2011b; Li et al., 2017). Furthermore, there are a number of studies that have focused only on the peak flows, where they projected increases in the magnitude of flooding in California under climate change scenarios (e.g., Das et al., 2011a, 2013; Dettinger and Ingram, 2012). The aim of the current study is to get a more comprehensive view of possible changes in streamflow distribution over Northern California by analyzing the possible changes in different streamflow quantiles. Unlike previous studies, and instead of gridded runoff simulations, we employed a unique data set generated for the 4th California Climate Assessment group, which includes climate model simulations, bias corrected, and routed for 59 sites across Northern California for the period of 1950–2099. Moreover, in order to investigate the direction of change in river discharge, in addition to investigating the mean flows, we examine changes over different parts of the discharge regime (from low to high flows).

2. Data and method

Daily streamflow (m^3/s) data for 59 locations across Northern California were developed at the Scripps Institution of Oceanography, University of California San Diego and acquired from the 4th California Climate Assessment group (Pierce et al., 2014, 2015; Fig. S1). The Variable Infiltration Capacity (VIC) land surface model (Lohmann et al., 1996, 1998), a macro-scale hydrological model framework that simulates surface and subsurface processes, was forced with downscaled global climate model (GCM) simulations to route streamflow at a daily temporal scale by using the Saint-Venant equations.

The use of downscaling techniques to convert the coarse spatial resolution in the GCMs to high resolution hydrological variables is an inevitable step for the climate change impacts assessment studies (Mehrotra and Sharma, 2015). Climate model simulations are submit to biases and uncertainties (e.g., Liu et al., 2014) and bias correction methods are often used to improve the forcings Pierce et al. (2014, 2015). Here, the VIC model is driven by the high-resolution Localized Constructed Analogs (LOCA) downscaled and bias-corrected minimum and maximum temperature, and precipitation. LOCA method has shown a superior performance to its predecessors including Multivariate Adapted Constructed Analogs (MOCA) for California and the 4th California Climate Assessment workforce is adopting it for policy making and climate adaptation purposes (Pierce et al., 2014). The LOCA method calculates the simulated hydrological variable by using a multiscale spatial matching framework in order to select suitable analog days from historical observations for each downscaled point. This is in oppose to using an average of several days to reproduce the downscaled products. The LOCA method calculates the simulated hydrological variable by using a multiscale spatial matching framework in

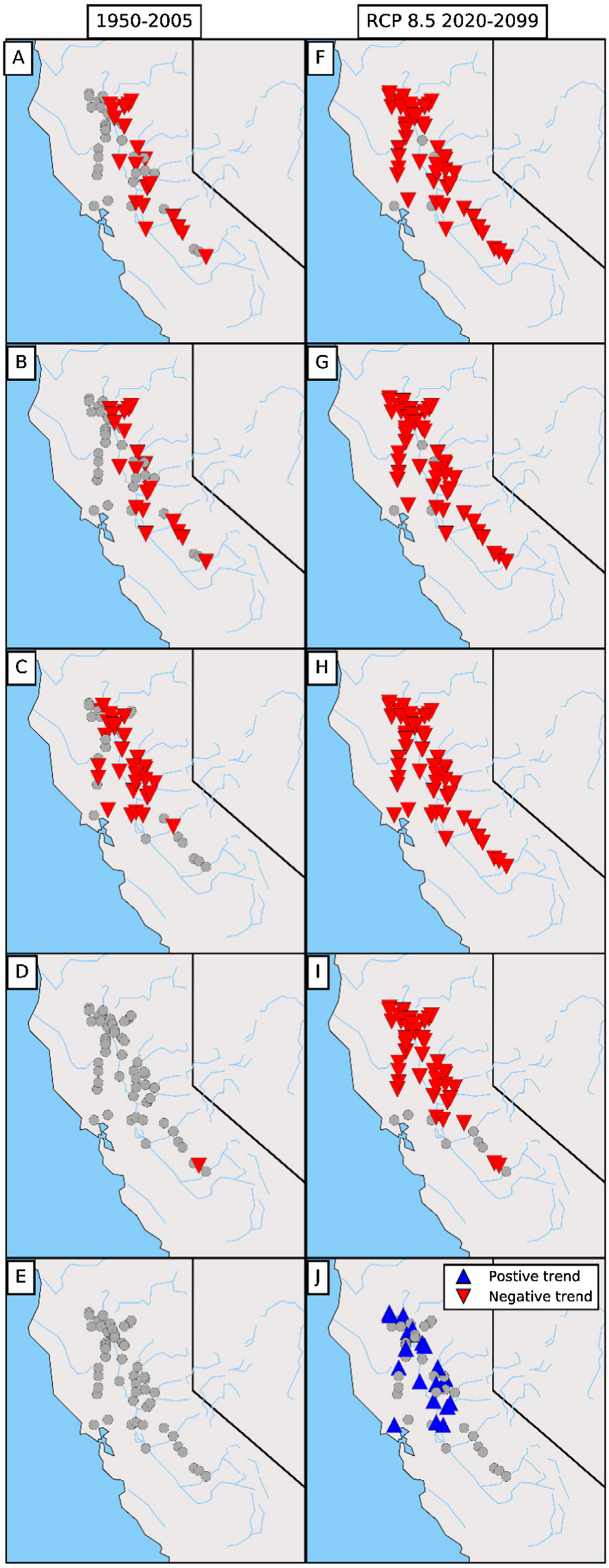

Fig. 3. Trends in the magnitude of different discharge quantiles: Q0.05 (panels A and F), Q0.25 (panels B and G), Q0.50 (panels C and H), Q0.75 (panels D and I), and Q0.95 (panels E and J). Left panels depict the baseline period whereas the right panels represent future projections (RCP 8.5). Positive and negative trends are presented with upward blue, and downward red triangles, respectively. Grey circles show the sites with no statistically significant trends at 0.05 level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

order to pick suitable analog days from historical observations. Pierce et al. (2014) mentioned that the motivation behind developing the LOCA method was to have a framework that can better preserve regional patterns in temperature and precipitation, and also better represent the maximum temperature and precipitation for California. There are a number of limitations associated with the use of any downscaling technique including simplification of the physical processes that may result in systematic errors that can be distributed between temperature and precipitation (Mehrotra and Sharma, 2012, 2016). More detailed description of the downscaling and bias-correction methods to develop the streamflow dataset we used here, together with limitations and advantages, can be found in Pierce et al. (2014, 2015).

The VIC model utilized the high resolution LOCA temperature and precipitation (with a grid resolution of 0.0625°) to obtain different hydroclimate variables such as daily streamflow. The VIC model parameters were obtained from the University of Colorado hydrologically based dataset for entire California (Livneh et al., 2013; Maurer et al., 2002). The VIC physical-based hydrological model solves the full water and energy balances equation and can represent the hydrological responses of the system to climatic changes including the soil moisture responses to the rainfall event (Maurer et al., 2018). This widely used hydrological model has shown a great success in simulating several large scale continental rivers (e.g., Nijssen et al., 1997), as well as regional smaller-scale rivers (e.g., Lohmann et al., 1998). The details on the VIC model, together with strengths, weakness and parameterization of it can be found in the Pierce et al. (2016). As Pierce et al. (2016) indicated while the VIC hydrological modeling framework is widely used in the hydrological community, the use of any hydrological model will result in some degree of uncertainty to projected climate variables and future studies are encouraged to perform similar analysis using additional land surface models. Furthermore, it is noteworthy that the antecedent moisture conditions in a drying climate were merely accounted for by the energy balance scheme of the VIC model, and further uncertainty analysis is required to scrutinize such impacts on the trends of streamflow. This will be the subject of a future study.

In this study, the bias-corrected inputs to the VIC model are based on ten GCMs from the Fifth Coupled Model Intercomparison Project (CMIP5; Table S1) and two representative concentration pathways (RCPs): RCP4.5 and RCP8.5. We use these ten models, selected from 32 different GCMs by the Climate Action Team Research Working Group of the 4th California's Climate Change Assessment, as they cover a wide range of possible conditions that California may confront in the future (CDWR, 2015). Furthermore, the future climate related policies and actions in California would be based on the outputs of these climate models that is provided by the 4th California's Climate Change Assessments (www.ClimateAssessment.ca.gov).

For each site and scenario, we calculated the ensemble median of daily streamflow based on all the ten climate models from 1950 to 2099 using 1950 to 2005 as the historical baseline period and 2020 to 2099 as the projection period. To investigate changes in the magnitude and direction of discharge, we computed annual time series for different discharge quantiles (from low to high flows) of the daily streamflow for each of the 59 locations (Lins and Slack, 1999; Villarini and Strong, 2014). We then use the nonparametric Mann-Kendall test (Kendall and Gibbons, 1990; Mann, 1945) to detect monotonic trends in different parts of the streamflow distribution. An extensive discussion on the Mann-Kendall test can be found in Helsel and Hirsch (1992). The test evaluates the null hypothesis (H_0) of no statistically significant change against the alternative hypothesis (H_a) of a statistically significant trend in the time series at 0.05 significance (95% confidence) level. We also examined the projected change in the magnitude and direction of river discharge based on two hydrological indices, namely 7-day peak flow and 7-day low flow (see Supplementary Material Section S1; Monk et al., 2007; Olden and Poff, 2003; Richter et al., 1996, 1998). Finally, we used the projected change in the mean monthly flows to compare

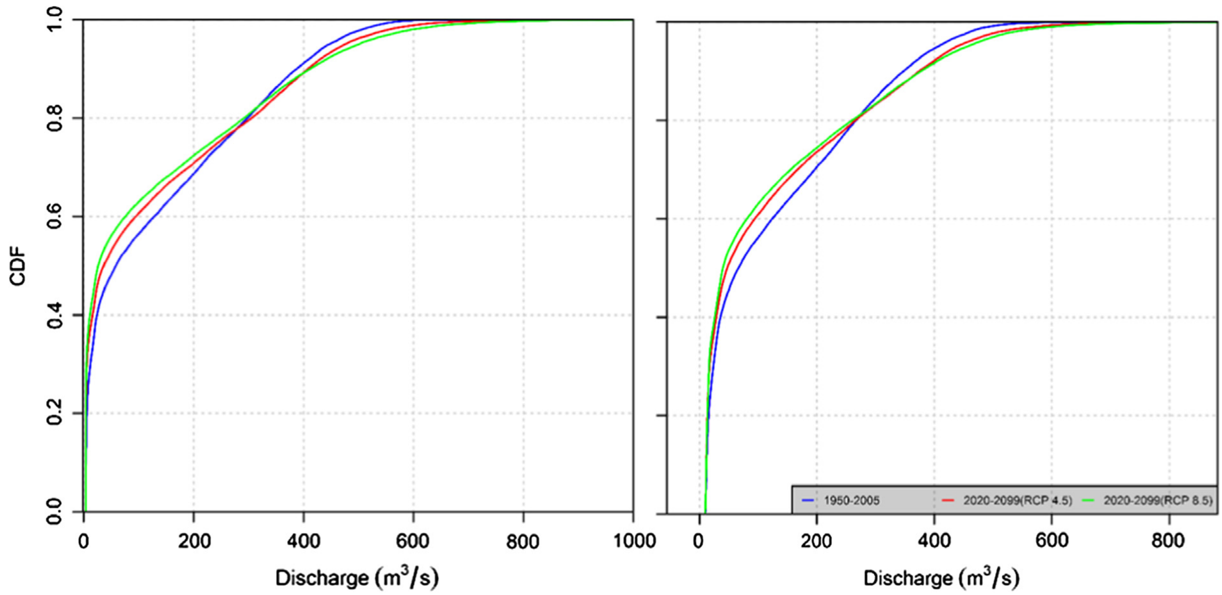

Fig. 4. Empirical Cumulative Distribution Functions (ECDFs) of streamflow in the baseline (blue line) and projection periods (red line RCP 4.5 and green line RCP 8.5) in the Oroville Lake (left panel) and Shasta Lake (right panel). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the streamflows over the wet seasons versus the warm seasons to get insight about the possible seasonal changes in streamflow. We compared the mean of the hydrological indices in the projection period relative to the baseline period under the RCP 4.5 and 8.5 by computing normalized percent change: ($\frac{Future - Historical}{Historical} \times 100$).

3. Results

Fig. 1 shows presence/absence of statistically significant trends, at 5% level, in the annual mean (panel A-C), annual minima (panel D-F) and annual maxima (panel G-I) of ensemble median of daily streamflow data. Overall, out of the 59 locations, none exhibits statistically significant changes in the annual mean of daily streamflow for both the historical forcing (Fig. 1A) and the RCP 4.5 scenario (Fig. 1B). Similar behavior is observed for the RCP8.5 scenario, with only 2 locations showing statistically significant changes in the annual mean of streamflow (Fig. 1C). Lack of pronounced signal of change in the annual mean discharge is also observed when we explore trends in the annual volume of ensemble daily streamflow data (Fig. S2). These results are consistent with previous studies revealing that future annual mean flow and annual volume of water are not projected to change significantly relative to the baseline (e.g., Regonda et al., 2005; Stewart et al., 2005; Thorne et al., 2015).

However, trends and patterns fundamentally change when investigating the upper and lower tails of the streamflow distribution. Fig. 1D–E show the changes in the magnitude of annual minima. Although the signal of change is relatively weak for the historical period (Fig. 1E; only 8 out of 59 sites show statistically significant change), it becomes much stronger when we explore changes in the projection period. As shown, 19 and 54 sites (out of 59) exhibit statistically significant decreasing trends in the discharge annual minima under the RCP 4.5 (Fig. 1E) and 8.5 (Fig. 1F) scenarios, respectively. Investigating annual maxima reveals opposing trends: 27 sites show statistically significant increasing trends in the baseline period, whereas 29 and 55 sites exhibit statistically significant increasing trends under the RCP 4.5 (Fig. 1H) and RCP 8.5 (Fig. 1I) scenarios, respectively. Therefore, climate models point to a widespread decreasing (increasing) trends in the annual minima (maxima) over Northern California. Under the RCP 8.5 scenario changes in the annual minimum and maximum discharge are larger and widespread over the entire Northern California.

To get a more detailed picture on how the tails of discharge distribution are changing, we investigate percent changes in the projected mean of 7-day low flows (Fig. 2A and C) and 7-day high flows (Fig. 2B and D) relative to the historical period. Fig. 2 depicts that the magnitudes of 7-day low flows are projected to slightly decrease for both concentration paths relative to the baseline, and changes are marginally higher under the RCP 8.5 (Fig. 2C). Considering the magnetite of 7-day high flows (Fig. 2B and D), most locations exhibit pronounced increasing patterns. It is worth mentioning that the magnitude of change is higher under RCP 8.5 relative to RCP 4.5. Most of the stations that show slightly decreasing trends in the magnitude of 7-day high flows are located in the southern part of the study region.

To this end, our analysis points to a decreasing trend in the magnitude of low flows and increasing trend in the magnitude of high flows. To further explore this issue, we investigate how the distribution of river discharge is expected to change under global warming. We extend our analysis to examine the presence of monotonic trends over different discharge quantiles (i.e., Q0.05, Q0.25, Q0.5, Q0.75, Q0.95) using the Mann-Kendall test. Here, we only show the results for RCP 8.5 for brevity, and similar results for RCP 4.5 can be found in Fig. S3. Fig. 3 shows that the future projections point to statistically significant decreasing trends in the streamflow relative to the baseline period for the 5th, 25th, 50th and 75th percentiles. While in the baseline period we do not observe a statistically significant change for the 95th percentiles of discharge, a significant increasing trend for the 95th percentile of projections is observed consistent with the previous figures. These trends are most prevalent over the northern part of the study area. Fig. 3 confirms that current climate model simulations indicate an asymmetrical change in the tails of the streamflow distribution; i.e. low flows decrease and high flows increase.

The change in the distribution of streamflow is more evident by looking at Fig. 4 which presents the Empirical Cumulative Distribution Functions (ECDFs) of the ensemble median of daily streamflow in the baseline and projection periods for two locations: Oroville Lake (Fig. 4A) and Shasta Lake (Fig. 4B). The projected streamflow ECDFs confirm the results from Fig. 3 and show the potential changes in different parts of the discharge distribution. The discharge below the 80th percentiles exhibits a lower low flow, while it indicates higher high flows above the 80th percentiles.

To understand the seasonal changes, we have also investigated

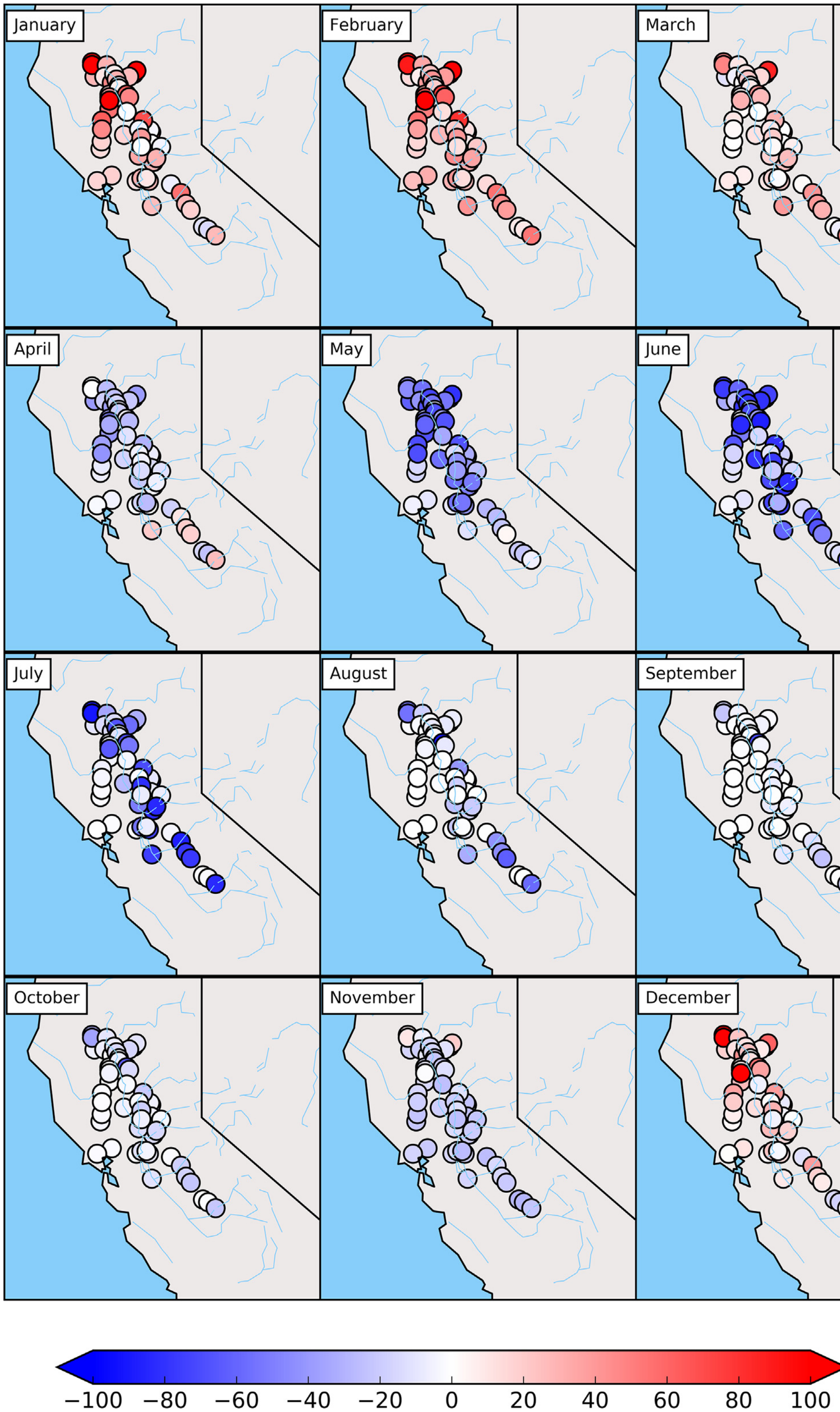

Fig. 5. Percent change [%] in the mean of the monthly river discharge under RCP 8.5 relative to the baseline period.

percent changes in the projected mean of streamflows relative to the baseline period at the monthly scale (Figs. 5 and S4). During the winter months (December, January, and February) and March (when most of the annual precipitation is delivered), majority of the sites depict an increase in the monthly mean of projected streamflow. This increasing pattern is more prevalent for the sites that are located in the north part of the study region over the Sacramento River Basin. In the rest of the year (April to November), the results point to a marked decrease in the mean of streamflow relative to the baseline period, with deviation from the mean being more pronounced in April to July. Overall, these results show that mean monthly streamflows over the rainy season are projected to increase by the end of the century under RCP 8.5 (similar

results for RCP 4.5 shown in Fig. S4), while for the rest of the year a decreasing trend is expected. This indicates California can possibly face wetter wet seasons and drier dry seasons by the end of this century. This finding is in line with Pierce et al. (2013) that projected an increase in winter average precipitation in California. Note that these changes in the mean monthly streamflows are more noticeable for the higher emissions scenario (RCP 8.5; Fig. S5).

4. Discussion and conclusion

In this study, we explore potential changes in future river flows in California using bias-corrected and routed simulated streamflows from multi-model climate simulations. Our results indicate that the annual mean of daily streamflow is not expected to change significantly by the end of this century. However, we observe opposing trends and sign of change when examining changes in the upper and lower tails of streamflow distribution. Results point to a widespread statistically significant increase in the magnitude of the annual streamflow maxima and a prevalent decreasing trend in the annual streamflow minima under both RCP 4.5 and RCP 8.5 scenarios. Investigating 7-day low and high flows and different quantiles of streamflow distribution also confirm this finding, indicating that extreme high and low flows are expected to intensify while the mean flows are not expected to change significantly. Overall, the decreasing (increasing) trends in the magnitude of 7-day high flows are vivid in the southern (northern) part of the study domain. Our results are in agreement with Yoon et al. (2015) who postulated future changes in large scale circulation patterns might intensify future floods and droughts. Our findings are also consistent with Li et al. (2017) who pointed to declines in low to moderated discharge in the future. However, in contrast to Li et al. (2017), our analysis does not identify a statistically significant change in the annual mean streamflow. Instead, we only find an increasing pattern in the magnitude of high flows.

We also examine projected changes in the mean of monthly streamflow relative to the baseline period. Model simulations show that while annual mean of daily streamflow is not projected to significantly change, mean of monthly streamflow is projected to increase during most of the rainy season (December to March) and to decrease in the dry season. This increasing signal is more pronounced for the sites that are located in the Sacramento River Basin. In other words, not only the distribution of streamflow, but also the seasonality of river discharge is projected to change by the end of this century. Note that, as Wasko and Sharma (2017) indicated, the response of streamflow to an extreme precipitation event depends on the catchment size, and extreme precipitation events at a higher temperature level may not necessarily result in higher streamflow. Our results here indicate that in the future, California can face wetter rainy seasons, and drier dry seasons as indicated. Moreover, Das et al. (2011b) have shown the important role of warm season warming versus cool season warming on the streamflow level in the western United States. They projected a higher reduction in streamflow under warmer warm season and an increase in the streamflow under warmer cool season. Therefore, projected changes in the mean of monthly streamflow will be of key importance for improving our strategies to manage water resources in California.

While attribution of the projected changes in discharge is not the main focus of this study, a possible explanation for the observed changes in river discharge is that low to moderate flow in rivers is sustained primarily by snow, with snowpack decreasing in the western United States and snowmelt happening earlier in spring (Huning and Margulis, 2017; Maurer et al., 2007; Mote et al., 2005; Stewart et al., 2005). Stewart et al. (2005) examined the seasonality of streamflow in snowmelt-dominated regions of western North America from 1948 to 2002 where they pointed to a reduction of spring and summer streamflow due to earlier snowmelt. For the northern part of California, Pierce et al. (2013) projected an increase in daily precipitation intensity in the winter season while spring precipitation is projected to decrease that can worsen the impact of earlier snowpack melting on the water resources. A smaller contribution of snowmelt to streamflow and also reduction in the ratio of snow over rain can lead to lower low to moderate discharge during seasons with lower precipitation (Li et al., 2017; Mote et al., 2005). Moreover, Diffenbaugh et al. (2015) indicated that snowpack in the montane regions of California has an important role in sustaining river discharge during the dry season. However, the projected increase in temperatures, and consequently earlier snowmelt can result in elongated dry and low flow periods (Ashfaq et al., 2013; Diffenbaugh et al., 2015; Li et al., 2017; Stewart et al., 2005). Li et al. (2017) showed that historically one-third of precipitation over the entire western United States falls as snow, which accounts for more than half of the total annual streamflow. They projected that smaller fraction (~%40 to %30) of snowmelt will contribute to annual discharge in the future. Furthermore, they argued that runoff will be more rainfall driven in the future over California. On the other hand, high flow events might be mainly controlled by moist and warm extreme AR events (Dettinger, 2011; Jeon et al., 2015). An extensive discussion on the impacts of warming climate on ARs can be found in Espinoza et al. (2018) where they indicated that all the studies conducted over western United States point to an increase in the frequency of AR events in a changing climate. Moreover, in a recent study, Ragno et al. (2018) showed that future extreme precipitation events are expected to intensify in California, despite relatively unchanged precipitation mean. Their findings are consistent with our results on future changes to the high flows.

Projected changes in California's streamflows can have profound implications for water resource management and infrastructure design and risk assessment. This issue becomes even more important considering the already aging infrastructures (e.g., dams, levees, and bridges) designed based on historical extremes and the assumption of stationarity. Any shift in high flows in the future would increase the risk of infrastructure failure or damages to critical structures such as the 2017 failure of the Oroville Dam spillway. Therefore, new methodological frameworks are needed to incorporate potential projected changes in the current infrastructure design and risk assessment procedures to lower the risk of infrastructure failures in the future.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2018.10.023.

References

AghaKouchak, A., Cheng, L., Mazdiyasni, O., Farahmand, A., 2014. Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California

drought. Geophys. Res. Lett. 41 (24). https://doi.org/10.1002/2014GL062308.

Alfieri, L., Burek, P., Feyen, L., Forzieri, G., 2015. Global warming increases the frequency of river floods in Europe. Hydrol. Earth Syst. Sci. 19 (5), 2247–2260. https://doi.org/10.5194/hess-19-2247-2015.

Ashfaq, M., Ghosh, S., Kao, S.-C., Bowling, L.C., Mote, P., Touma, D., et al., 2013. Near-term acceleration of hydroclimatic change in the western U.S. J. Geophys. Res.: Atmos. 118 (19), 10676–10693. https://doi.org/10.1002/jgrd.50816.

Barth, N.A., Villarini, G., Nayak, M., White, K., 2016. Mixed populations and annual flood frequency estimates in the western United States: the role of atmospheric rivers. n/a-n/a. Water Resour. Res. https://doi.org/10.1002/2016WR019064.

Beighley, R.E., Melack, J.M., Dunne, T., 2003. Impacts of California's climatic regimes and coastal land use change on streamflow characteristics1. JAWRA J. Am. Water Resour. Assoc. 39 (6), 1419–1433. https://doi.org/10.1111/j.1752-1688.2003.tb04428.x.

Berghuijs, W.R., Woods, R.A., Hrachowitz, M., 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. Nat. Clim. Change 4 (7), 583–586. https://doi.org/10.1038/nclimate2246.

Burke, W.D., Ficklin, D.L., 2017. Future projections of streamflow magnitude and timing differ across coastal watersheds of the western United States: PROJECTED STREAMFLOW MAGNITUDE AND TIMING IN THE COASTAL WESTERN US. Int. J. Climatol. https://doi.org/10.1002/joc.5099.

Cayan, D.R., Dettinger, M.D., Kammerdiener, S.A., Caprio, J.M., Peterson, D.H., 2001. Changes in the onset of spring in the Western United States. Bull. Am. Meteorol. Soc. 82 (3), 399–415. https://doi.org/10.1175/1520-0477(2001)082<0399:CITOOS>2.3.CO;2.

CDWR, 2015. Perspectives and Guidance for Climate Change Analysis. Retrieved from. California Department of Water Resources and Climate Change Technical Advisory Group.

Cheng, L., AghaKouchak, A., Gilleland, E., Katz, R.W., 2014. Non-stationary extreme value analysis in a changing climate. Clim. Change 127 (2), 353–369. https://doi.org/10.1007/s10584-014-1254-5.

Das, T., Dettinger, M.D., Cayan, D.R., Hidalgo, H.G., 2011a. Potential increase in floods in California's Sierra Nevada under future climate projections. Clim. Change 109 (1), 71–94. https://doi.org/10.1007/s10584-011-0298-z.

Das, T., Pierce, D.W., Cayan, D.R., Vano, J.A., Lettenmaier, D.P., 2011b. The importance of warm season warming to western U.S. streamflow changes: WARM SEASON WARMING STREAMFLOW CHANGES. Geophys. Res. Lett. 38 (23), n/a-n/a. https://doi.org/10.1029/2011GL049660.

Das, T., Maurer, E.P., Pierce, D.W., Dettinger, M.D., Cayan, D.R., 2013. Increases in flood magnitudes in California under warming climates. J. Hydrol. 501, 101–110. https://doi.org/10.1016/j.jhydrol.2013.07.042.

Demaria, E.M.C., Palmer, R.N., Roundy, J.K., 2016. Regional climate change projections of streamflow characteristics in the Northeast and Midwest U.S. J. Hydrol.: Reg. Stud. 5, 309–323. https://doi.org/10.1016/j.ejrh.2015.11.007.

Dettinger, M., 2011. Climate change, atmospheric rivers, and floods in California – a multimodel analysis of storm frequency and magnitude changes 1: Climate. JAWRA J. Am. Water Resour. Assoc. 47 (3), 514–523. https://doi.org/10.1111/j.1752-1688.2011.00546.x.

Dettinger, M.D., Ingram, B.L., 2012. The coming megafloods. Sci. Am. 308 (1), 64–71. https://doi.org/10.1038/scientificamerican0113-64.

Diffenbaugh, N.S., Swain, D.L., Touma, D., 2015. Anthropogenic warming has increased drought risk in California. Proc. Natl. Acad. Sci. 112 (13), 3931–3936. https://doi.org/10.1073/pnas.1422385112.

Espinoza, V., Waliser, D.E., Guan, B., Lavers, D.A., Ralph, F.M., 2018. Global analysis of climate change projection effects on atmospheric rivers. Geophys. Res. Lett. 45 (9), 4299–4308. https://doi.org/10.1029/2017GL076968.

Hailegeorgis, T.T., Alfredsen, K., 2017. Regional flood frequency analysis and prediction in ungauged basins including estimation of major uncertainties for mid-Norway. J. Hydrol.: Reg. Stud. 9, 104–126. https://doi.org/10.1016/j.ejrh.2016.11.004.

Hardin, E., et al., 2017. California drought increases CO_2 footprint of energy. Sustain. Cities Soc. 28, 450–452. https://doi.org/10.1016/j.scs.2016.09.004.

Harpold, A.A., Rajagopal, S., Crews, J.B., Winchell, T., Schumer, R., 2017. Relative humidity has uneven effects on shifts from snow to rain over the western U.S. Geophys. Res. Lett. 44 (19), 9742–9750. https://doi.org/10.1002/2017GL075046.

Helsel, D.R., Hirsch, R.M., 1992. Statistical Methods in Water Resources. Elsevier, Amsterdam.

Huning, L.S., Margulis, S.A., 2017. Climatology of seasonal snowfall accumulation across the Sierra Nevada (USA): accumulation rates, distributions, and variability. Water Resour. Res. 53 (7), 6033–6049. https://doi.org/10.1002/2017WR020915.

Jeon, S., Prabhat, Byna, S., Gu, J., Collins, W.D., Wehner, M.F., 2015. Characterization of extreme precipitation within atmospheric river events over California. Adv. Stat. Climatol. Meteorol. Oceanogr. 1 (1), 45–57. https://doi.org/10.5194/ascmo-1-45-2015.

Kendall, M.G., Gibbons, J.D., 1990. Rank correlation methods, fifth ed. E. Arnold; Oxford University Press, London: New York, NY.

Knowles, N., Dettinger, M.D., Cayan, D.R., 2006. Trends in Snowfall versus Rainfall in the Western United States. J. Clim. 19 (18), 4545–4559. https://doi.org/10.1175/JCLI3850.1.

Koutsoyiannis, D., 2006. Nonstationarity versus scaling in hydrology. J. Hydrol. 324 (1–4), 239–254. https://doi.org/10.1016/j.jhydrol.2005.09.022.

Krakauer, N.Y., Fung, I., 2008. Mapping and attribution of change in streamflow in the coterminous United States. Hydrol. Earth Syst. Sci. 12 (4), 1111–1120. https://doi.org/10.5194/hess-12-1111-2008.

Leung, L.R., Qian, Y., 2009. Atmospheric rivers induced heavy precipitation and flooding in the western U.S. simulated by the WRF regional climate model: ATMOSPHERIC RIVER, PRECIPITATION, FLOOD. Geophys. Res. Lett. 36 (3), n/a-n/a. https://doi.org/10.1029/2008GL036445.

Li, D., Wrzesien, M.L., Durand, M., Adam, J., Lettenmaier, D.P., 2017. How much runoff originates as snow in the western United States, and how will that change in the future? Geophys. Res. Lett. 44 (12). https://doi.org/10.1002/2017GL073551.

Lins, H.F., Slack, J.R., 1999. Streamflow trends in the United States. Geophys. Res. Lett. 26 (2), 227–230. https://doi.org/10.1029/1998GL900291.

Liu, Z., et al., 2014. Seasonal and regional biases in CMIP5 precipitation simulations. Clim. Res. 60, 35–50. https://doi.org/10.3354/cr01221.

Livneh, B., Rosenberg, E.A., Lin, C., Nijssen, B., Mishra, V., Andreadis, K.M., et al., 2013. A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: update and extensions. J. Clim. 26 (23), 9384–9392. https://doi.org/10.1175/JCLI-D-12-00508.1.

Lohmann, D., Nolte-Holube, R., Raschke, E., 1996. A large-scale horizontal routing model to be coupled to land surface parametrization schemes. Tellus 48 (A), 708–721.

Lohmann, D., Raschke, E., Nijssen, B., Lettenmaier, D.P., 1998. Regional scale hydrology: II. Application of the VIC-2L model to the Weser River, Germany. Hydrol. Sci. J. 43 (1), 143–158. https://doi.org/10.1080/02626669809492108.

Luke, A., et al., 2017. Predicting nonstationary flood frequencies: evidence supports an updated stationarity thesis in the United States. Water Resour. Res. 53 (7), 5469–5494. https://doi.org/10.1002/2016WR019676.

Mallakpour, I., Villarini, G., 2015. The changing nature of flooding across the central United States. Nat. Clim. Change 5 (3), 250–254. https://doi.org/10.1038/nclimate2516.

Mallakpour, I., Villarini, G., Jones, M.P., Smith, J.A., 2017. On the use of Cox regression to examine the temporal clustering of flooding and heavy precipitation across the central United States. Global Planet. Change 155, 98–108. https://doi.org/10.1016/j.gloplacha.2017.07.001.

Mann, H.B., 1945. Nonparametric Tests Against Trend. Econometrica 13 (3), 245. https://doi.org/10.2307/1907187.

Mao, Y., Nijssen, B., Lettenmaier, D.P., 2015. Is climate change implicated in the 2013–2014 California drought? A hydrologic perspective. Geophys. Res. Lett. 42 (8). https://doi.org/10.1002/2015GL063456.

Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P., Nijssen, B., 2002. A long-term hydrologically based dataset of land surface fluxes and states for the Conterminous United States*. J. Clim. 15 (22), 3237–3251. https://doi.org/10.1175/1520-0442(2002) 015<3237:ALTHBD>2.0.CO;2.

Maurer, E.P., Stewart, I.T., Bonfils, C., Duffy, P.B., Cayan, D., 2007. Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. J. Geophys. Res. 112 (D11). https://doi.org/10.1029/2006JD008088.

Maurer, E.P., Kayser, G., Doyle, L., Wood, A.W., 2018. Adjusting flood peak frequency changes to account for climate change impacts in the Western United States. J. Water Resour. Plan. Manag. 144, 05017025. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000903.

McCabe, G.J., Wolock, D.M., 2014. Spatial and temporal patterns in conterminous United States streamflow characteristics. Geophys. Res. Lett. 41 (19). https://doi.org/10.1002/2014GL061980.

Mehrotra, R., Sharma, A., 2012. An improved standardization procedure to remove systematic low frequency variability biases in GCM simulations: TECHNICAL NOTE. Water Resour. Res. 48 (12). https://doi.org/10.1029/2012WR012446.

Mehrotra, R., Sharma, A., 2015. Correcting for systematic biases in multiple raw GCM variables across a range of timescales. J. Hydrol. 520, 214–223. https://doi.org/10.1016/j.jhydrol.2014.11.037.

Mehrotra, R., Sharma, A., 2016. A multivariate quantile-matching bias correction approach with auto- and cross-dependence across multiple time scales: implications for downscaling. J. Clim. 29 (10), 3519–3539. https://doi.org/10.1175/JCLI-D-15-0356.1.

Milly, P.C.D., Dunne, K.A., Vecchia, A.V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438 (7066), 347–350. https://doi.org/10.1038/nature04312.

Monk, W.A., Wood, P.J., Hannah, D.M., Wilson, D.A., 2007. Selection of river flow indices for the assessment of hydroecological change. River Res. Appl. 23 (1), 113–122. https://doi.org/10.1002/rra.964.

Mote, P.W., Hamlet, A.F., Clark, M.P., Lettenmaier, D.P., 2005. Declining mountain snowpack in western north America. Bull. Am. Meteorol. Soc. 86 (1), 39–50. https://doi.org/10.1175/BAMS-86-1-39.

Nazemi, A., Wheater, H.S., 2014. Assessing the vulnerability of water supply to changing streamflow conditions. Eos Trans. Am. Geophys. Union 95 (32), 288. https://doi.org/10.1002/2014EO320007.

Neelin, J.D., Langenbrunner, B., Meyerson, J.E., Hall, A., Berg, N., 2013. California winter precipitation change under global warming in the coupled model intercomparison project phase 5 ensemble. J. Clim. 26 (17), 6238–6256. https://doi.org/10.1175/JCLI-D-12-00514.1.

Nijssen, B., Lettenmaier, D.P., Liang, X., Wetzel, S.W., Wood, E.F., 1997. Streamflow simulation for continental-scale river basins. Water Resour. Res. 33 (4), 711–724. https://doi.org/10.1029/96WR03517.

O'Gorman, P.A., Muller, C.J., 2010. How closely do changes in surface and column water vapor follow Clausius-Clapeyron scaling in climate change simulations? Environ. Res. Lett. 5 (2), 025207. https://doi.org/10.1088/1748-9326/5/2/025207.

Olden, J.D., Poff, N.L., 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Res. Appl. 19 (2), 101–121. https://doi.org/10.1002/rra.700.

Pachauri, R.K., Mayer, L., Intergovernmental Panel on Climate Change (Eds.), 2015. Climate change 2014: synthesis report. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Payne, A.E., Magnusdottir, G., 2015. An evaluation of atmospheric rivers over the North Pacific in CMIP5 and their response to warming under RCP 8.5: NORTH PACIFIC

ATMOSPHERIC RIVERS IN CMIP5. J. Geophys. Res.: Atmos. 120 (21), 11173–11190. https://doi.org/10.1002/2015JD023586.
Pierce, D., Cayan, D., Dehann, L., 2016. Creating Climate Projections to Support the 4th California Climate Assessment. Retrieved from. Division of Climate, Atmospheric Sciences, and Physical Oceanography Scripps Institution of Oceanography, La Jolla, CA.
Pierce, D.W., Cayan, D.R., Das, T., Maurer, E.P., Miller, N.L., Bao, Y., et al., 2013. The key role of heavy precipitation events in climate model disagreements of future annual precipitation changes in California. J. Clim. 26 (16), 5879–5896. https://doi.org/10.1175/JCLI-D-12-00766.1.
Pierce, D.W., Cayan, D.R., Thrasher, B.L., 2014. Statistical downscaling using localized constructed analogs (LOCA). J. Hydrometeorol. 15 (6), 2558–2585. https://doi.org/10.1175/JHM-D-14-0082.1.
Pierce, D.W., Cayan, D.R., Maurer, E.P., Abatzoglou, J.T., Hegewisch, K.C., 2015. Improved bias correction techniques for hydrological simulations of climate change*. J. Hydrometeorol. 16 (6), 2421–2442. https://doi.org/10.1175/JHM-D-14-0236.1.
Ragno, E., AghaKouchak, A., Love, C.A., Cheng, L., Vahedifard, F., Lima, C.H.R., 2018. Quantifying changes in future intensity-duration-frequency curves using multimodel ensemble simulations. Water Resour. Res. 54 (3), 1751–1764. https://doi.org/10.1002/2017WR021975.
Ralph, F.M., Coleman, T., Neiman, P.J., Zamora, R.J., Dettinger, M.D., 2013. Observed impacts of duration and seasonality of atmospheric-river landfalls on soil moisture and runoff in coastal northern California. J. Hydrometeorol. 14 (2), 443–459. https://doi.org/10.1175/JHM-D-12-076.1.
Read, L.K., Vogel, R.M., 2015. Reliability, return periods, and risk under nonstationarity. Water Resour. Res. 51 (8), 6381–6398. https://doi.org/10.1002/2015WR017089.
Regonda, S.K., Rajagopalan, B., Clark, M., Pitlick, J., 2005. Seasonal cycle shifts in hydroclimatology over the western United States. J. Clim. 18 (2), 372–384. https://doi.org/10.1175/JCLI-3272.1.
Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10 (4), 1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x.
Richter, B.D., Baumgartner, J.V., Braun, D.P., Powell, J., 1998. A spatial assessment of hydrologic alteration within a river network. Regul. Riv.: Res. Manage. 14 (4), 329–340. https://doi.org/10.1002/(SICI)1099-1646(199807/08)14:4 < 329::AID-RRR505 > 3.0.CO;2-E.
Sadegh, M., Vrugt, J.A., Xu, C., Volpi, E., 2015. The stationarity paradigm revisited: hypothesis testing using diagnostics, summary metrics, and $DREAM_{(ABC)}$: REVISITING SATIONARITY PARADIGM. Water Resour. Res. 51 (11), 9207–9231. https://doi.org/10.1002/2014WR016805.
Scheff, J., Frierson, D.M.W., 2014. Scaling potential evapotranspiration with greenhouse warming. J. Clim. 27 (4), 1539–1558. https://doi.org/10.1175/JCLI-D-13-00233.1.
Shukla, S., et al., 2015. Temperature impacts on the water year 2014 drought in California. Geophys. Res. Lett. 42 (11). https://doi.org/10.1002/2015GL063666.
Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2005. Changes toward earlier streamflow timing across western North America. J. Clim. 18 (8), 1136–1155. https://doi.org/10.1175/JCLI3321.1.
Thorne, J.H., Boynton, R.M., Flint, L.E., Flint, A.L., 2015. The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. Ecosphere 6 (2), 1–30. https://doi.org/10.1890/ES14-00300.1.
Vahedifard, F., AghaKouchak, A., Ragno, E., Shahrokhabadi, S., Mallakpour, I., 2017. Lessons from the Oroville dam. Science 355 (6330), 1139. https://doi.org/10.1126/science.aan0171.
Villarini, G., Strong, A., 2014. Roles of climate and agricultural practices in discharge changes in an agricultural watershed in Iowa. Agric. Ecosyst. Environ. 188, 204–211. https://doi.org/10.1016/j.agee.2014.02.036.
Villarini, G., Serinaldi, F., Smith, J.A., Krajewski, W.F., 2009. On the stationarity of annual flood peaks in the continental United States during the 20th century. Water Resour. Res. 45 (8), W08417. https://doi.org/10.1029/2008WR007645.
Villarini, G., Scoccimarro, E., White, K.D., Arnold, J.R., Schilling, K.E., Ghosh, J., 2015. Projected changes in discharge in an agricultural watershed in Iowa. JAWRA J. Am. Water Resour. Assoc. 51 (5), 1361–1371. https://doi.org/10.1111/1752-1688.12318.
Voss, R., May, W., Roeckner, E., 2002. Enhanced resolution modelling study on anthropogenic climate change: changes in extremes of the hydrological cycle. Int. J. Climatol. 22 (7), 755–777. https://doi.org/10.1002/joc.757.
Wang, G., Wang, D., Trenberth, K.E., Erfanian, A., Yu, M., Bosilovich, M.G., Parr, D.T., 2017. The peak structure and future changes of the relationships between extreme precipitation and temperature. Nat. Clim. Change. https://doi.org/10.1038/nclimate3239. advance online publication.
Wasko, C., Sharma, A., 2017. Global assessment of flood and storm extremes with increased temperatures. Sci. Rep. 7 (1). https://doi.org/10.1038/s41598-017-08481-1.
Yoon, J.-H., Wang, S.-Y.S., Gillies, R.R., Kravitz, B., Hipps, L., Rasch, P.J., 2015. Increasing water cycle extremes in California and in relation to ENSO cycle under global warming. Nat. Commun. 6, ncomms9657. https://doi.org/10.1038/ncomms9657.
Zhu, T., Jenkins, M.W., Lund, J.R., 2005. Estimated impacts of climate warming on California water availability under twelve future climate scenarios1. JAWRA J. Am. Water Resour. Assoc. 41 (5), 1027–1038. https://doi.org/10.1111/j.1752-1688.2005.tb03783.x.